

Overview and Recent Accomplishments of Advanced Mirror Technology Development Phase 2 (AMTD-2)

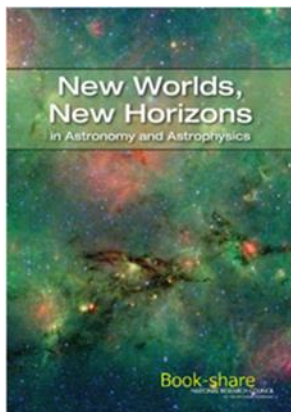
H. Philip Stahl, MSFC

AMTD is a funded NASA Strategic Astrophysics Technology (SAT) project

SPIE Conference on UV/Optical/IR Space Telescopes and Instrumentation, 2015



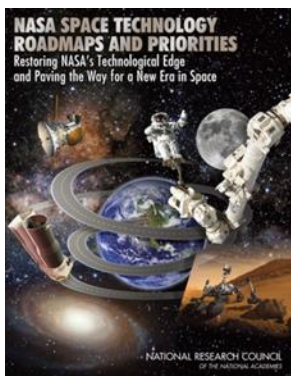
Future UVOIR Space Telescopes require Mirror Technology



Astro2010 Decadal Study recommended technology development (page 7-17) for a potential future:

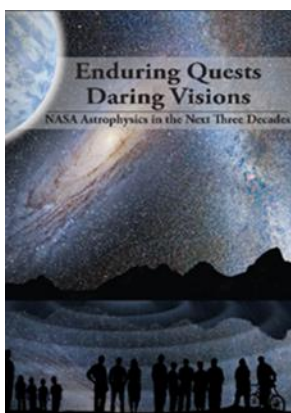
Exoplanet Mission (New-Worlds Explorer)

UVOIR Space Telescope (4 meter or larger)



2012 NASA Space Technology Roadmaps & Priorities: Top Technical Challenge C2 recommended:

New Astronomical Telescopes that enable discovery of habitable planets, facilitate advances in solar physics, and enable the study of faint structures around bright objects ...



2014 Enduring Quests Daring Visions recommended:

LUVOIR Surveyor with sensitivity to locate the bulk of planets in the solar neighborhood and reveal the details of their atmospheres.



Objective

AMTD's objective is to mature to TRL-6 the critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

Decadal 2010 called for technology development to enable a 4-m or larger UVOIR space telescope.

Both the General Astrophysics and Exoplanet Communities want the ability to perform high-contrast imaging and spectroscopy.

This probably requires a telescope larger than 4 meters.

AMTD is not developing technology for a specific mission.

Potential high-contrast imaging & spectroscopy architectures:

single aperture monolithic mirror telescope,

single aperture segmented mirror telescope,

sparse aperture, and

interferometers.



Multiple Technology Paths

Just as JWST's architecture was driven by launch vehicle, future mission's architectures (mono, segment or interferometric) will depend on capacities of future launch vehicles (and budget).

Since we cannot predict future, we must prepare for all futures.

To provide the science community with options, we are pursuing multiple technology paths for both monolithic and segmented aperture telescopes.

All potential UVOIR mission architectures (monolithic, segmented or interferometric) share similar mirror needs:

Very Smooth Surfaces

< 10 nm rms

Thermal Stability

Low CTE Material

Mechanical Stability

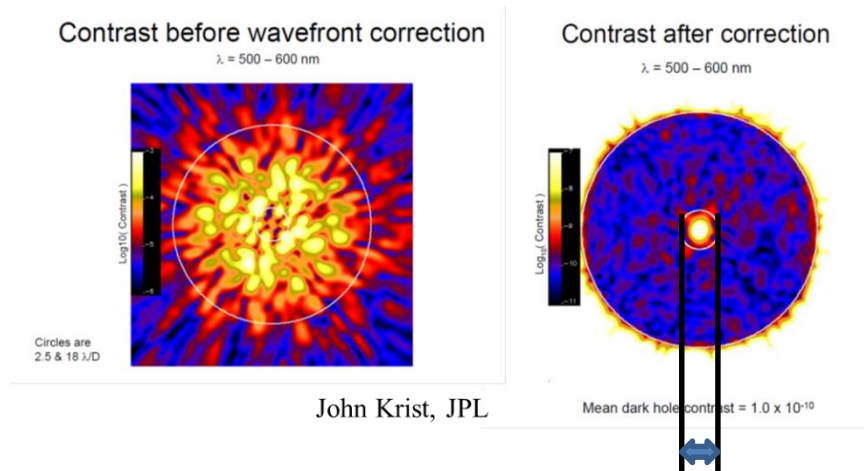
High Stiffness Mirror Substrates



‘The’ System Challenge: Dark Hole

Imaging an exoplanet, requires blocking 10^{10} of host star’s light

An internal coronagraph (with deformable mirrors) can create a ‘dark hole’ with $< 10^{-10}$ contrast.



Ultra-smooth, Ultra-Stable Mirror Systems are critical to achieving and maintaining the ‘dark hole’

Krist, Trauger, Unwin and Traub, “End-to-end coronagraphic modeling including a low-order wavefront sensor”, SPIE Vol. 8422, 844253, 2012; doi: 10.1117/12.927143

Shaklan, Green and Palacios, “TPFC Optical Surface Requirements”, SPIE 626511-12, 2006.



Technical Approach/Methodology

To accomplish our objective, we:

- Use a science-driven systems engineering approach.
- Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.

Mature Technology Simultaneous because all are required to make a primary mirror assembly (PMA); AND, it is the PMA's on-orbit performance which determines science return.

PMA stiffness depends on substrate and support stiffness.

Ability to cost-effectively eliminate mid/high spatial figure errors and polishing edges depends on substrate stiffness.

On-orbit thermal and mechanical performance depends on substrate stiffness, the coefficient of thermal expansion (CTE) and thermal mass.

Segment-to-segment phasing depends on substrate & structure stiffness.



Phase 1 & 2

Goals, Objectives & Tasks



Goals

To accomplish Objective, must mature 6 linked technologies:

Large-Aperture, Low Areal Density, High Stiffness Mirrors: 4 to 8 m monolithic & 8 to 16 m segmented primary mirrors require larger, thicker, stiffer substrates.

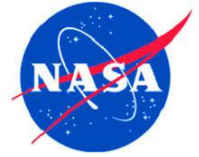
Support System: Large-aperture mirrors require large support systems to ensure that they survive launch & deploy on orbit in a stress-free & undistorted shape.

Mid/High Spatial Frequency Figure Error: A very smooth mirror is critical for producing a high-quality point spread function (PSF) for high-contrast imaging.

Segment Edges: Edges impact PSF for high-contrast imaging applications, contributes to stray light noise, and affects the total collecting aperture.

Segment-to-Segment Gap Phasing: Segment phasing is critical for producing a high-quality temporally stable PSF.

Integrated Model Validation: On-orbit performance is determined by mechanical & thermal stability. Future systems require validated models.



TRL Assessment

Before AMTD-1, we assessed the TRL of each key technology.

We revisited assessment based on AMTD-1 accomplishments and anticipated AMTD-2 accomplishments.

Technology Readiness Assessment				
Technology	Metric	Before AMTD-1	Current	After AMTD-2
Large-Aperture, Low Areal Density, High Stiffness Substrate	1.5-m Seg	TRL6 (AMSD/MMSD) ^{note 1}	-	TRL6 (1.5mDC&1.2mZerodur) ^{note 2}
	4-m Mono	TRL2 (subscale 2.4 m HST) TRL5 (8 m Ground)	TRL3 (43 cm Deep Core) -	TRL4 (1.5m Deep Core) -
Support System	Segment	TRL3 (JWST is not UVOIR)	-	TRL3 (8-m Point Design)
	Monolithic	TRL6 (subscale 1.4 m Kepler) TRL5 (8 m Ground)	TRL6 (4-m Point Design) TRL5 (8-m Point Design)	TRL6 (4-m Point Design) TRL5 (8-m Point Design)
Mid/High Spatial Frequency Error	< 4nm rms	TRL5 (HST, 8 m Ground)	TRL6 (43 cm @ 250K)	TRL6 (1.5m & 1.2m at 250K)
Segment Edges	Polished	TRL6 (2 mm demonstrated)	X	X
	Apodize	TRL2	TRL3 (BNL demo)	X
Segment-to-Segment Gap Phasing	Alignment	TRL3 (JWST is not UVOIR)	TRL3.5 (2 stage Actuator)	X
	Stability	TRL0 (<10 pm rms stability)	X	X
Integrated Model Validation	Structural	TRL4/5 (JWST & SVMV)	TRL4/5 (43 cm Gravity)	TRL5 (1.5 m Modal & Gravity)
	Thermal	TRL4/5 (JWST & SVMV)	TRL4/5 (43 cm Thermal)	TRL5 (1.5 m Thermal)
	Optical	TRL4/5 (JWST & SVMV)	-	TRL4/5 (GSFC Tool)

NOTE 1: AMSD/MMSD Exelis mirror was manufactured from ULE©. Other AMSD mirrors were manufactured from Be & Fused Silica.

NOTE 2: AMTD-2 achieving TRL6 for Segmented requires unfunded Strength, Vibration & Acoustic Test of 1.5 m Deep Core & 1.2 m Zerodur



Key

Done

Stopped

In-Process

Not Started Yet

Phase 1: Goals, Progress & Accomplishments

Systems Engineering:

- derive from science requirements monolithic mirror specifications
- derive from science requirements segmented mirror specifications

Large-Aperture, Low Areal Density, High Stiffness Mirror Substrates:

- make a subsection mirror via a process traceable to 500 mm deep mirrors

Support System:

- produce pre-Phase-A point designs for candidate primary mirror architectures;
- demonstrate specific actuation and vibration isolation mechanisms

Mid/High Spatial Frequency Figure Error:

- ‘null’ polish a 1.5-m AMSD mirror & subscale deep core mirror to a < 6 nm rms zero-g figure at the 2°C operational temperature.

Segment Edges:

- demonstrate an achromatic edge apodization mask

Segment to Segment Gap Phasing:

- develop models for segmented primary mirror performance; and
- test prototype passive & active mechanisms to control gaps to ~ 1 nm rms.

Integrated Model Validation:

- validate thermal model by testing the AMSD and deep core mirrors at 2°C
- validate mechanical models by static load test.



Phase 1: Key Accomplishments

Derived from Science Requirements, Engineering Specifications for Primary Mirror Wavefront Error and Stability

Demonstrated, at the 0.5-m scale, the ability to make mechanically stiff, i.e. stable, UVOIR traceable mirrors:

- <6 nm rms surface
- 60-kg/m²
- 400-mm deep-core substrate

using the stack-core low-temperature-fusion/low-temperature-slumping (LTF/LTS) process.

Developed Tools for Integrated Modeling and Model Verification.



Phase 2: Tasks

Refine engineering specifications for a future monolithic or segmented space telescope based on science needs & implementation constraints.

Mature 4 inter-linked critical technologies.

Large-Aperture, Low Areal Density, High Stiffness Mirrors

Fabricate a 1/3rd scale model of a 4-m class 400 mm thick deep-core ULE© mirror – to demo lateral scaling.

Support System – continue Phase A design studies

Mid/High Spatial Frequency Figure Error

Test 1/3rd scale ULE© & 1.2 m Zerodur Schott mirror at 280K

Integrated Model Validation – continue developing and validating tools



Phase 2: Tasks

Key
Done
Stopped
In-Process
Not Started Yet

Monolithic Mirror Substrate Technology

Fabricate and test A-Basis allowable required for mirror

Design 1/3-scale model of a 4-m x 400-mm class ~150Hz ULE[®] mirror

Design support structure for Zerodur 1.2m mirror

Mirror Preparation

Fabricate & polish 1/3-scale model ULE mirror & support structure

Fabricate support structure & Polish Zerodur mirror

Thermal Characterization

“Qualify” (i.e., test) two candidate lightweight primary mirrors (1.35m or 1.5m Harris & 1.2m Zerodur Schott) in X-Ray & Cryogenic Facility at MSFC

Characterize their optical performance from 250K to ambient

Expose to representative vibration and acoustic launch environments & conduct modal test of both mirrors



Phase 2: Tasks

Key
Done
Stopped
In-Process
Not Started Yet

Integrated Design, Modeling and Analysis

- Predict thermal, vibe and acoustic behavior of the two mirrors in test

- Predict on-orbit performance

- Investigate optimized mechanical design methods

Environmental Performance Model Validation

- Validate thermal and mechanical models

On-orbit Optical Performance Predictions

- Increase capability to design and analysis tools to predict on-orbit performance (PSF, jitter, encircled energy, wavefront error, MTF, etc.)

Design Optimization Methods

- Use on-orbit optical performance metrics to investigate parametric optimization (e.g., radius of curvature, thickness, bending, aspheric prescription, spacing, etc. effects on PSF, EE, Zernikes, residual WFE)

Pre-Phase A 4m Point Designs

- Extrapolate validated models to generate refined Pre-Phase A point designs for 4m mirrors on potential launch vehicles (i.e., EELV, Falcon 9 and SLS for approximately 5 mirror variants)

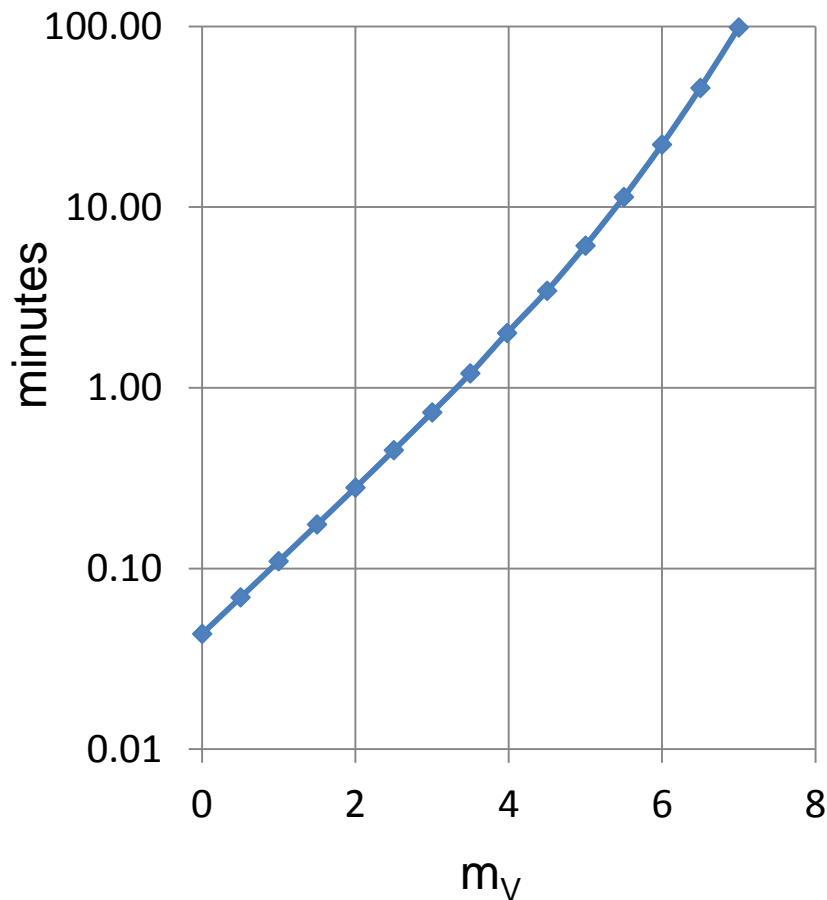


Engineering Specifications

Wed Aug 12, 9:00 am: Preliminary analysis of effect of random segment errors on coronagraph performance; Mark T. Stahl, H. Philip Stahl, Stuart B. Shaklan



Integration Time for a 10 m telescope



Simulation Parameters

$\Delta\text{mag} = 25$ (to control background level)

Spectral Resolution = 10

SNR = 3 per channel

Throughput 42%

QE 80%

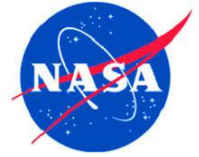
No detector noise

Instrument contrast = $1e-10$

Zodi + exozodi = 3×23 mag/sq. arcsec

Wavelength 760 nm

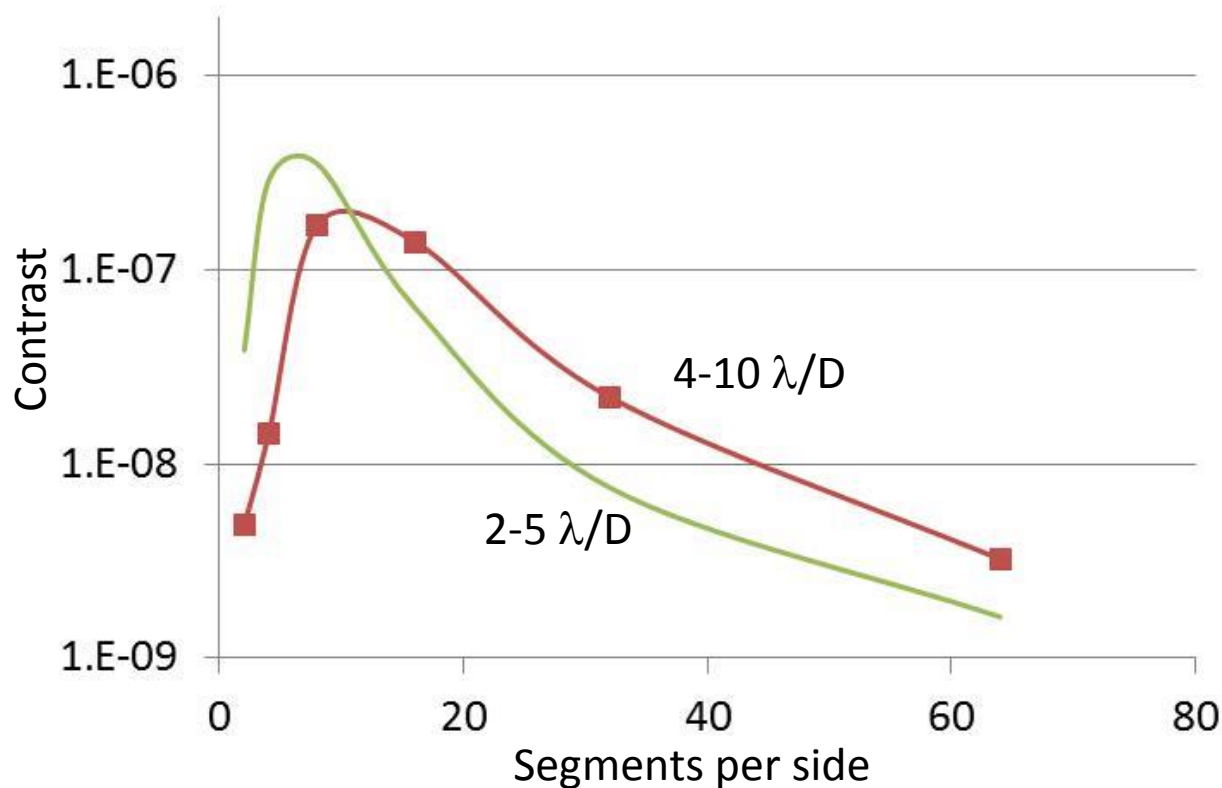
Sharpness 0.08



Contrast vs. Number of Segments

1 nm tip/tilt rms per segment

Contrast evaluated between $2-5 \lambda/D$ and $4-10 \lambda/D$.



Square telescope

2x2, 4x4, 8x8...64x64 segments across square aperture.

1 nm rms tip/tilt wavefront, $\lambda=600$ nm.

Coronagraph mask is 2-D $1-\text{sinc}^2$, first transmission max at $4 \lambda/D$



Large-Aperture, Low-Areal Density, High-Stiffness Mirror Substrates

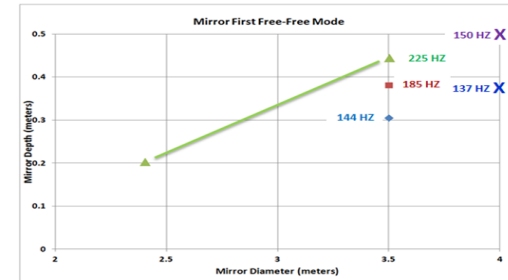
Mon Aug 10, 1:40 pm: Status of the Advanced Mirror Technology Development (AMTD) phase 2 1.5m ULE mirror; Robert M. Egerman, Gary W. Matthews, Albert J. Ferland, Matthew Johnson



Large Substrate: Technical Challenge

Future large-aperture space telescopes (regardless of monolithic or segmented) need ultra-stable mechanical and thermal performance for high-contrast imaging.

This requires larger, thicker, and stiffer substrates.



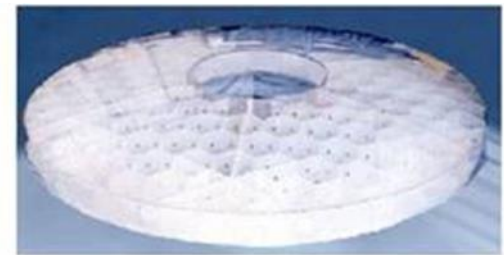
Current launch vehicle capacity limits requires low areal density.

State of the Art is

ATT Mirror: 2.4 m, 3-layer, 0.3 m deep, 24 kg/m²; LTF as sphere

AMSD ULE©: 1.4 m, 3 layer, 0.06m deep, 13 kg/m²; LTF & LTS

Kepler: 1 m, frit bonded



Harris 2.4 m ATT Mirror



Large Substrate: Achievements

Successfully demonstrated a new fabrication process (stacked core low-temperature fusion).

Process offers significant cost and risk reduction. It is difficult (and expensive) to cut a deep-core substrate to exacting rib thickness requirements. Current SOA is ~300 mm on an expensive custom machine; commercial machines can cut < 130 mm cores.

Extended state of the art for deep core mirrors from less than 300 mm to greater than 400 mm.

Successfully 're-slumped' a ULE© fused substrate.

This allows generic substrates to be assembled and placed in inventory for re-slumping to a final radius of curvature.

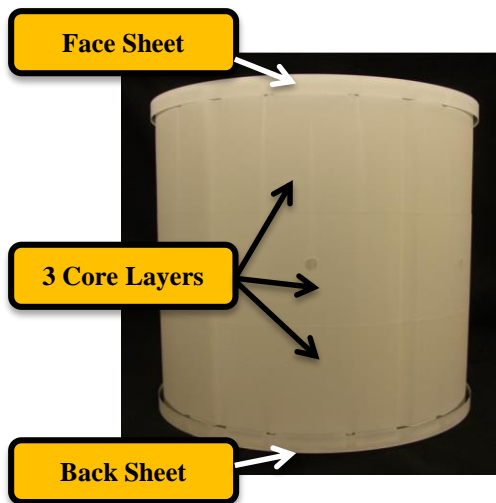
Quantified Strength of Stack-Core LTF process components.



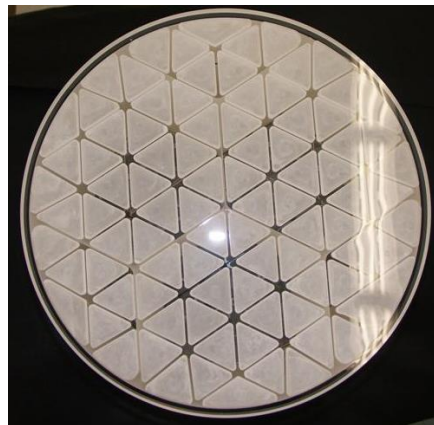
43 cm Deep Core Mirror

Harris successfully demonstrated 5-layer 'stack & fuse' technique which fuses 3 core structural element layers to front & back faceplates.

Made 43 cm 'cut-out' of a 4 m dia, > 0.4 m deep, 60 kg/m^2 mirror substrate.



Post-Fusion Side View
3 Core Layers and Vent Hole Visible



Post-Fusion Top View
Pocket Milled Faceplate



Post Slump:
2.5 meter Radius of Curvature

This technology advance leads to stiffer 2 to 4 to 8 meter class substrates at lower cost and risk for monolithic or segmented mirrors.

Matthews, Gary, et al, *Development of stacked core technology for the fabrication of deep lightweight UV quality space mirrors*, SPIE Conference on Optical Manufacturing and Testing X, 2013.



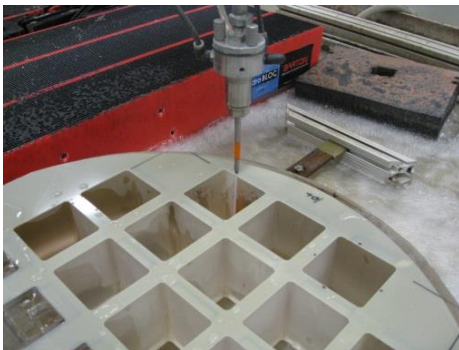
Strength Testing

AMTD-1: Harris strength tested the core to core LTF bond strength on 12 Modulus of Rupture (MOR) test articles.

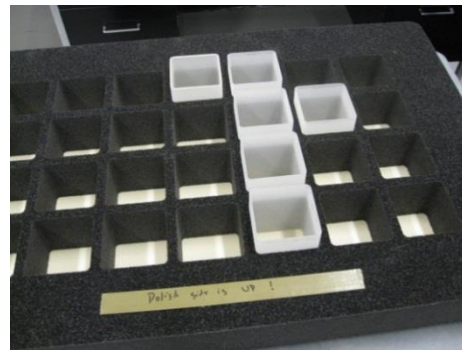
- Weibull 99% survival value was 15% above conservative design allowable. Data ranged from 30% to 200% above design allowable.

AMTD-2: A-Basis test of core rib to core rib LTF bond strength.

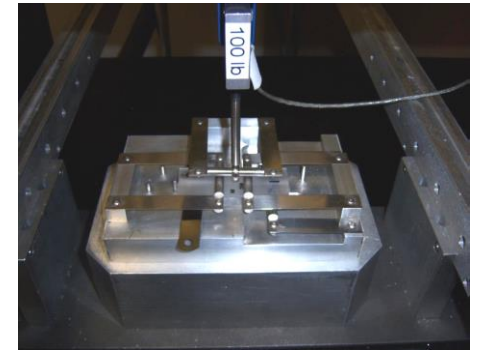
- 60+ MOR Samples: 30+ samples aligned; 30+ core misaligned
- A-basis Weibull 99% confidence strength allowable for 49 samples is 17.5MPa; ~50% higher than the strength of core-to-plate LTF bonds.



MOR Boxes in Abrasive Water Jet (AWJ)



post AWJ, pre-LTF assembly



MOR sample in Test Fixture



Phase 2: Demonstrates Lateral Scaling

Demonstrate lateral scaling of 'stacked-core' to larger diameter

Approximately 1/3rd scale model of a 4 meter mirror

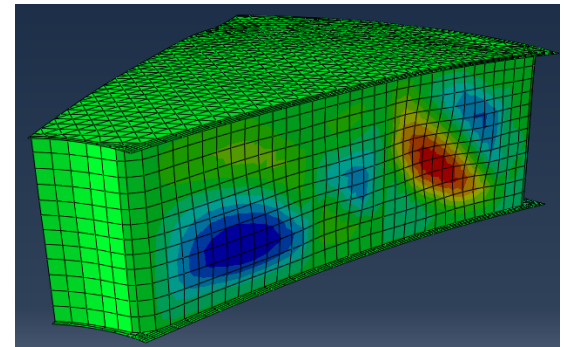
1.5m class diameter and about 200mm thick

(2) ULE® face plates

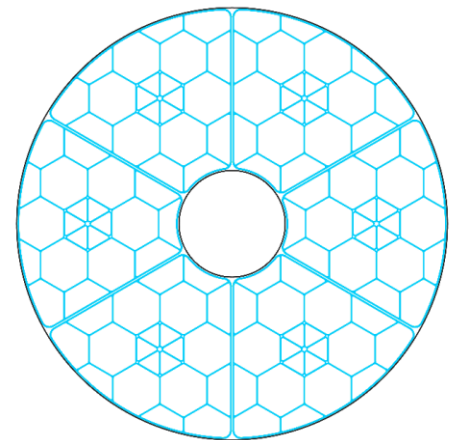
(3) ULE® glass boules

On-axis

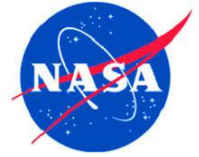
Non-linear visco-elastic tools and methods
used to design 4-m class mirror, then
scaled to 1.5-m



**Completed: design for ~1/3 scale mirror
blank of 4m class UVOIR Primary
Mirror with solid facesheets.**

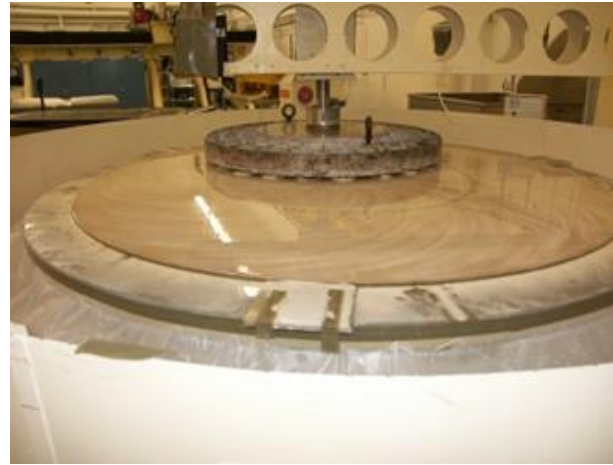


Courtesy: Harris

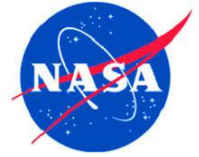


Phase 2: Fabrication Status

The Face-plates have been cut to size and are being polished.



Water jet cutting of the 18 core elements will start in September.



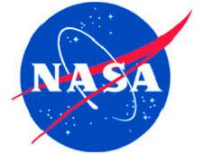
Mid/High Spatial Frequency Figure Error

Mon Aug 10, 11:00 am: Measuring skew in average surface roughness as function of surface preparation; Mark T. Stahl



Integrated Model Validation

Sun Aug 9, 4:00 pm: Thermal optical metrology development for large lightweight UV to IR mirrors and future space observatory missions; Ron Eng, Markus A. Baker, William D. Hogue, Jeffrey R. Kegley, Richard D. Siler, H. Philip Stahl, John M. Tucker, Ernest R. Wright



Support System & Design Tools

Wed Aug 12, 9:30 am: Evolving design criteria for very large aperture space-based telescopes and their influence on the need for integrated tools in the optimization process; William R. Arnold, Sr.

Wed Aug 12, 9:50 am: Recent updates to the Arnold Mirror Modeler and integration into the evolving NASA overall design system for large space-based optical systems; William R. Arnold, Sr.



Support System

Technical Challenge:

- Large-aperture mirrors require large support systems to survive launch & deploy on orbit in a stress-free and undistorted shape.

Accomplishments:

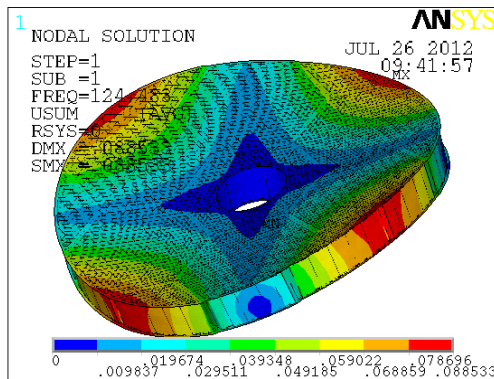
- Developed a new modeler tool for ANSYS which can produce 400,000-element models in minutes.
- Tool facilitates transfer of high-resolution mesh to mechanical & thermal analysis tools.
- Used our new tool to compare pre-Phase-A point designs for 4-meter and 8-meter monolithic primary mirror substrates and supports.



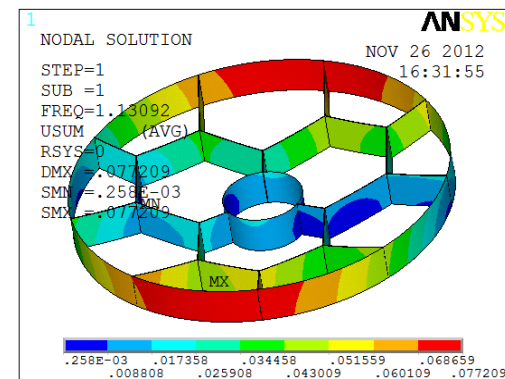
Design Tools and Point Designs

AMTD has developed a powerful tool which quickly creates monolithic or segmented mirror designs; and analyzes their static & dynamic mechanical and thermal performance.

Point Designs: AMTD has used these tools to generate Pre-Phase-A point designs for 4 & 8-m mirror substrates.

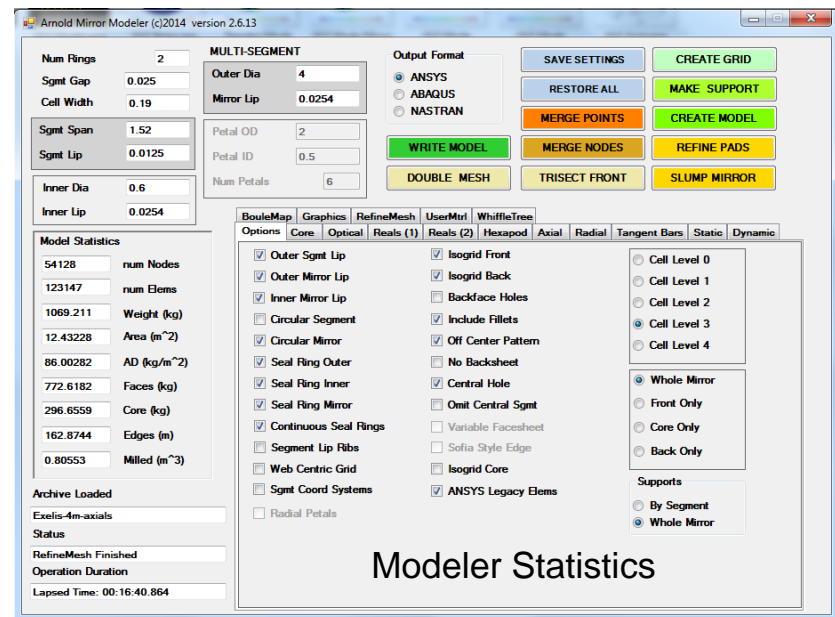
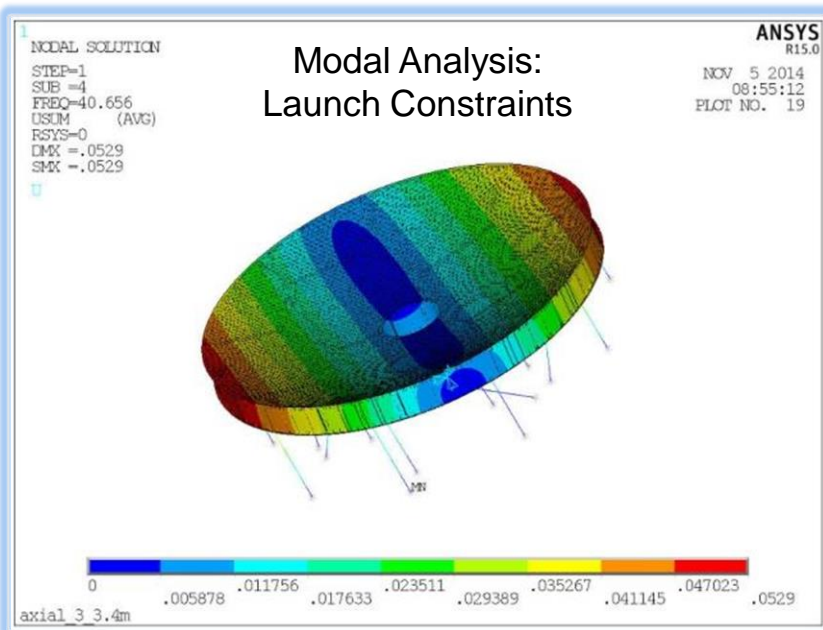
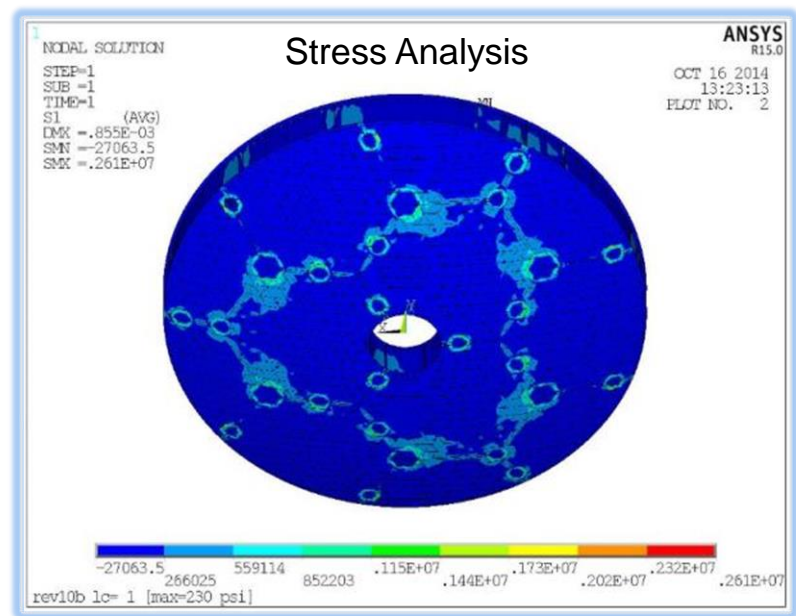
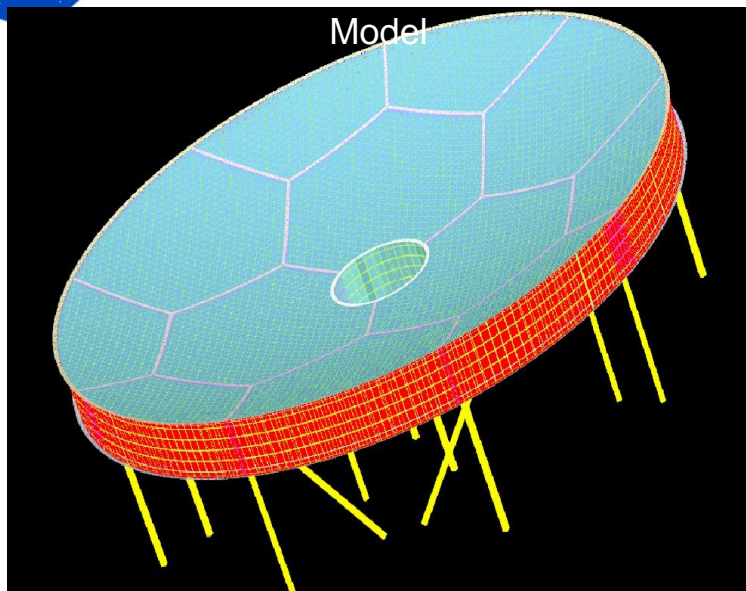


Free-Free 1st Mode: 4 m dia 40 cm thick substrate



Internal Stress: 4 m dia with 6 support pads

Support System: AMTD has used these tools to generate Pre-Phase-A point designs for 4-m mirror substrate with a launch support system.

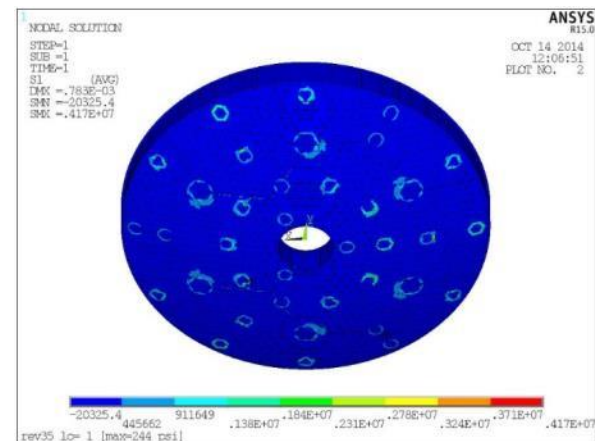




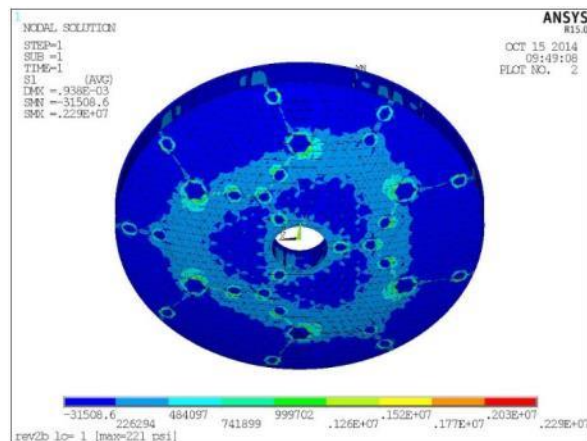
ULE Mirror

Different layouts were tried for the Axial supports. Initial trials spread the supports out evenly across the mirror

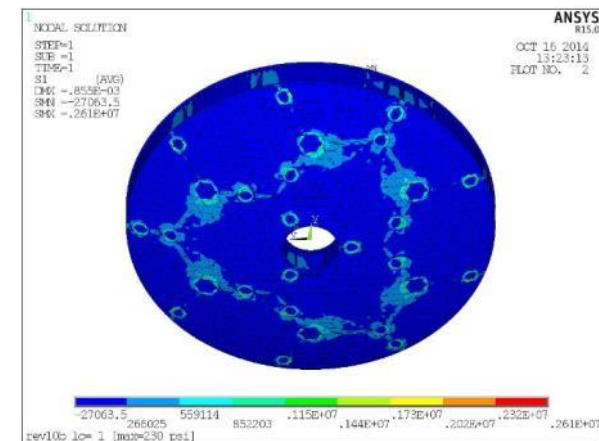
Most optimal design placed supports along the segment intersections. Additionally, even spacing helped avoid ‘pressure points.’



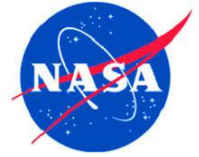
31 supports,
244 psi



24 supports,
221 psi



21 supports,
230 psi



75 Hz and 50 Hz Design Points

Tough Decisions: Mass Savings vs. Decreased rigidity

Lower frequency obtained by decreasing mirror core thickness

While 75 Hz or even 50 Hz aren't ideal, they give designers more options

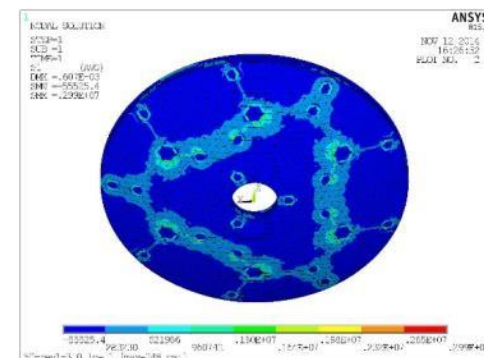
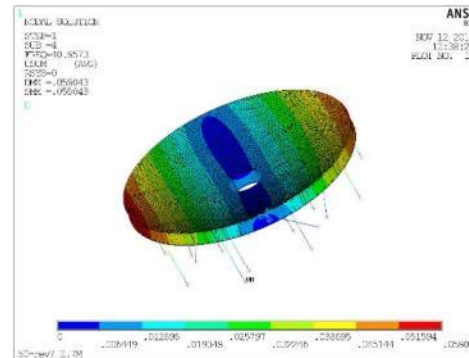
Frequency

Frequency (Hz)

Core Thickness (m)

75 Hz:
6.75 in thick
820.8 kg

21
supports,
244 psi



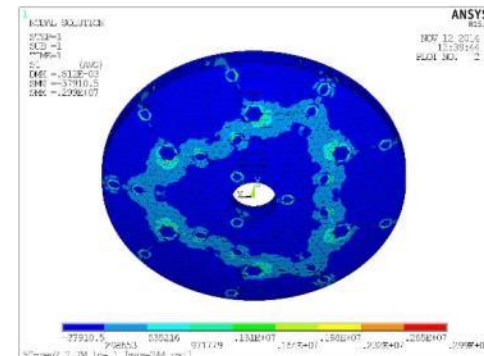
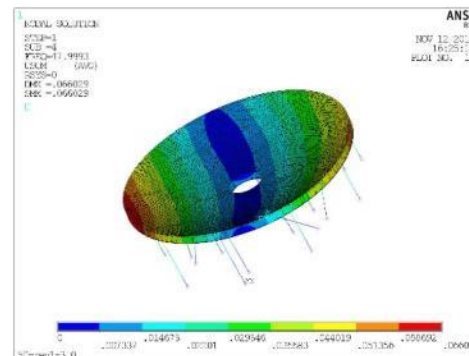
Mass

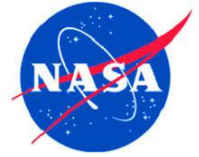
Mass (kg)

Core Thickness (m)

50 Hz:
3.125 in thick
727.0 kg

21
supports,
248 psi





Integrated Modeling Tools

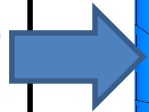
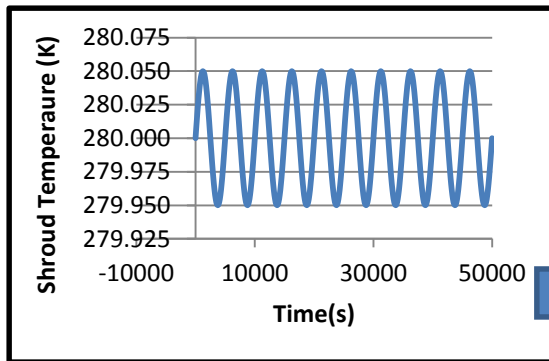
Thurs Aug 13, 8:20 am: Advanced Mirror Technology Development (AMTD) thermal trade studies; Thomas Brooks, H. Philip Stahl, William R. Arnold, Sr., Brent Knight, Mike R. Effinger, W. Scott Smith

Thurs Aug 13, 8:40 am: AMTD: Advanced mirror technology development in mechanical stability; Joseph B. Knight



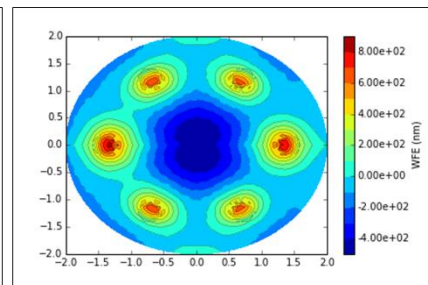
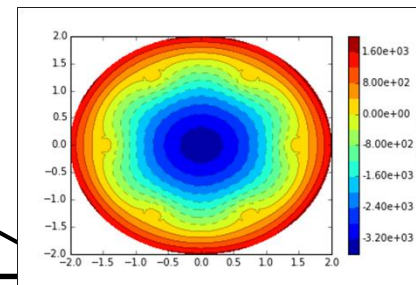
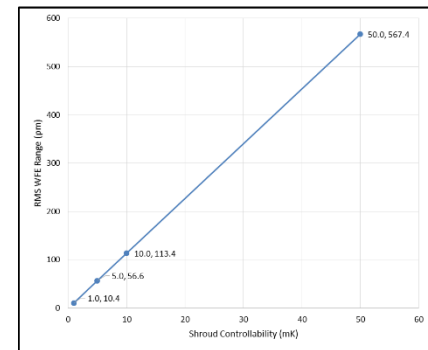
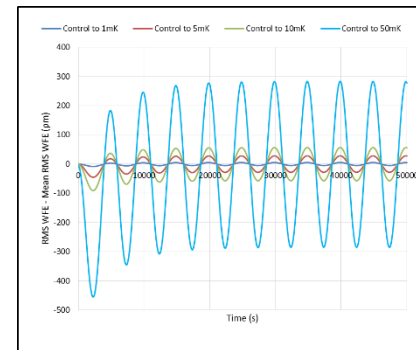
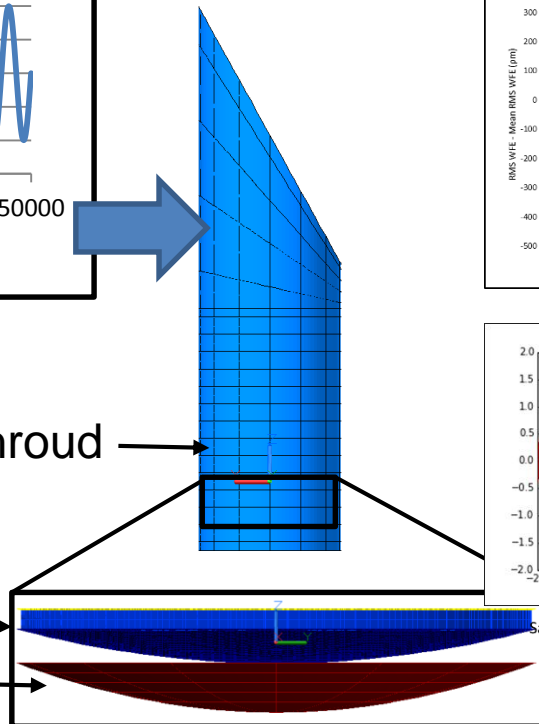
Thermal Stability Study

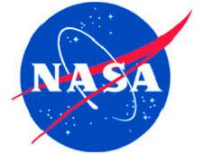
- Understand how primary mirror responds to dynamic external thermal environment.
- Specify how to control telescope thermal environment to keep primary mirror stable to better than 10 pm per 10 minutes



Thermal Shroud

Mirror
Heater





Segment to Segment Gap Phasing

Gersh-Range, Jessica; William R. Arnold, Sr.; H. Philip Stahl, “Edgewise connectivity: an approach to improving segmented primary mirror performance”, Journal of Astronomical Telescope and Instrument Systems, (2014) DOI: 10.1117/1.JATIS.1.1.014002

Gersh-Range, Jessica; William R. Arnold, Sr.; David Lehner; H. Philip Stahl, “Flux-pinning mechanisms for improving cryogenic segmented mirror performance”, Journal of Astronomical Telescope and Instrument Systems, (2014) DOI: 10.1117/1.JATIS.1.1.014001



Segment to Segment Gap Phasing

Technical Challenge:

- Diffraction limited performance requires ‘co-phased’ segments.
- Segment to Segment motion degrades exoplanet contrast performance.
 - To avoid speckle noise which can interfere with exo-planet observation, Internal coronagraphs require segment to segment dynamic co-phasing error < 10 pm rms between WFSC updates.

Achievement

- AMTD developed a model to investigate the effect of edgewise connectivity with dampening to improve dynamic mirror performance.
- AMTD investigated mechanism technology to ‘phase’ segments.
 - Woofer/Tweeter two-stage actuator
 - Flux-Pinning Interface
 - Correlated Magnetic interface



Two-Stage Actuation Mechanism

Demonstrated Fine Rigid Body Actuator (FRBA) at Harris

Completed assembly and testing of flight traceable FRBA

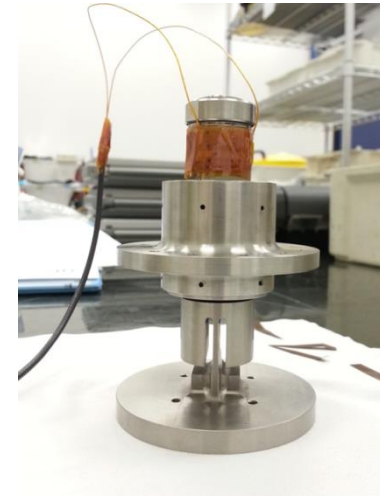
Demonstrated compliance with all requirements except resolution

Demonstrated the 'fine' stage of a low mass two stage actuator which could be used co-phase segments

Ability to verify actual resolution was limited by test set & electronics design

Using improved low noise electronics will enable requirement to be achieved

Property	Performance
Mass	0.313 Kg
Axial stiffness	40.9 N/ μ m
Test Range	14.1 μ m
Resolution	6.6 nm (noise limited result) [expected is 0.8 nm]
Accuracy	1.1 μ m

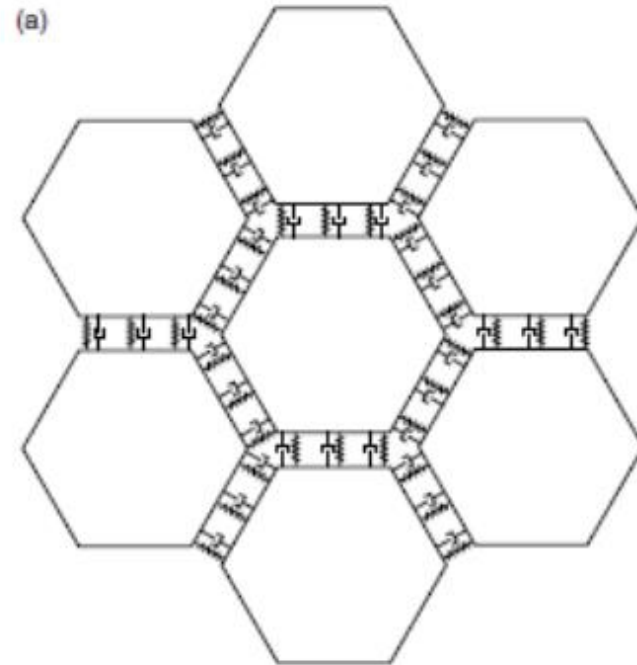




Segment Dynamic Motion

Rapid Random Segment rigid body motion (Piston & Tip/Tilt) reduces dark hole contrast by moving energy from the core into speckles and diffraction spikes.

Connecting segments together at the edges with damped spring interfaces provides potentially significant performance advantages for very large mirrors.



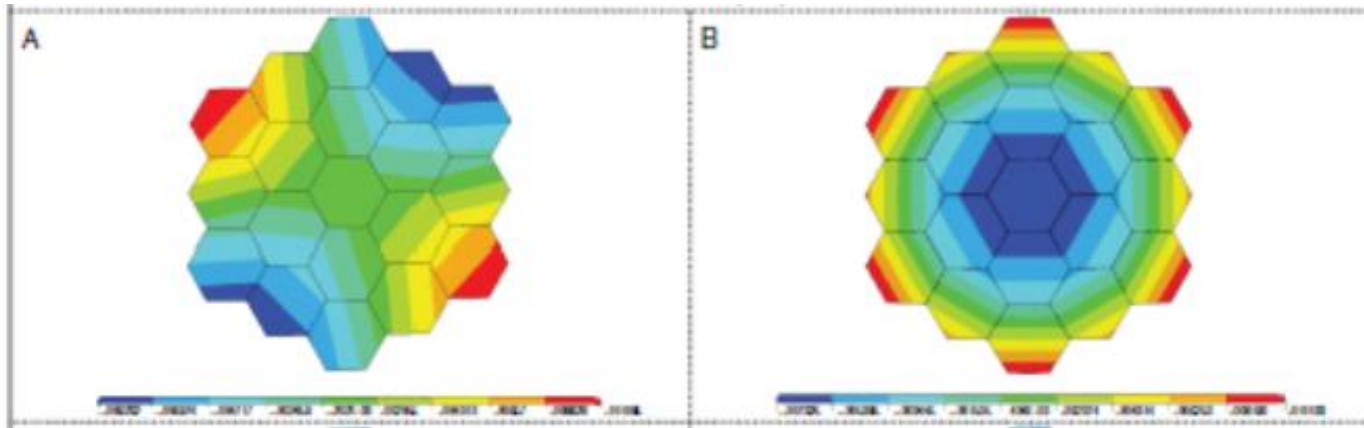


Segmented Mirror Dynamic Motion

With no edgewise connectivity, segments behave independently.

With as few as 3 edgewise damped spring interfaces, the segments start to act as a monolith.

Adjusting spring stiffness tunes the assembly's first mode frequency proportional to square root of interface stiffness, but approaches monolithic performance asymptotically.





Segmented Mirror Dynamic Motion

By adjusting stiffness & dampening, a segmented mirror stabilizes faster to a impulse than a monolith.

Low to Intermediate Stiffness does not propagate waves.

High Dampening reduces wave amplitude quickly.

More segment rings perform slightly better than fewer.

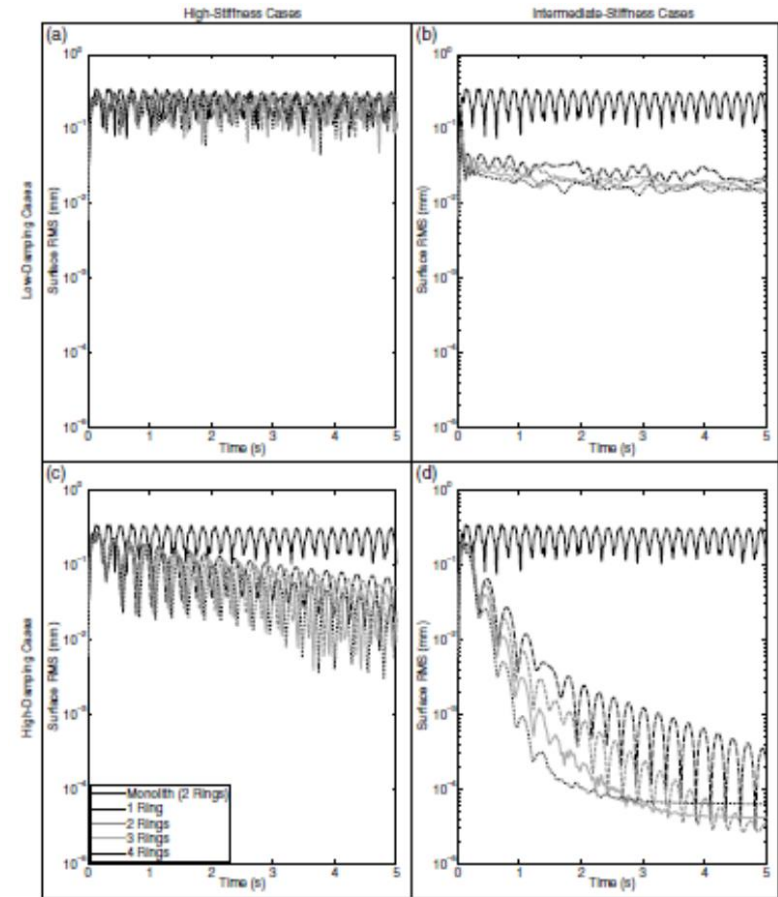
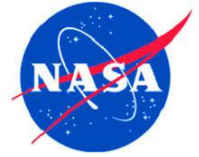


Fig. 9 The effects of ring number on the impulse response for various mechanism cases (a-d).



Conclusions

AMTD uses a science-driven systems engineering approach to define & execute a long-term strategy to mature technologies necessary to enable future large aperture space telescopes.

Because we cannot predict the future, we are pursuing multiple technology paths including monolithic & segmented mirrors.

Assembled outstanding team from academia, industry & government; experts in science & space telescope engineering.

Derived engineering specifications from science measurement needs & implementation constraints.

Maturing 6 critical technologies required to enable 4 to 8 meter UVOIR space telescope mirror assemblies for both general astrophysics & ultra-high contrast exoplanet imaging.

AMTD achieving all its goals & accomplishing all its milestones